Why does air passage over forest yield more rain? Alternative interpretations of Spracklen et al. 2012 *Nature* 489: 282

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Abstract

Spracklen et al. recently presented a pan-tropical study of rainfall and land-cover that showed that satellite-derived rainfall measures were positively correlated with the degree to which model-derived air trajectories had been exposed to forest cover. This result confirms the influence of vegetation on regional rainfall patterns suggested in previous studies. However, we find that the conclusion of Spracklen et al. – that differences in rainfall reflect air moisture content resulting from evapotranspiration – appears undermined by methodological inconsistencies. We discuss some alternative explanations that require investigation. These include the distinct role of forest evapotranspiration in creating low pressure systems that draw moisture from the oceans to the continental hinterland. This alternative physical process is consistent with the empirical findings of Spracklen et al. but underlines a greater potential danger of forest loss than is suggested by their analyses of moisture recycling.

1 Introduction

In their recent pan-tropical study Spracklen et al. [2012] examined how air exposure to forest cover influences subsequent rainfall from air moving over the tropical land surface. The positive association found confirms the influence of vegetation on regional rainfall patterns suggested in previous studies [Makarieva and Gorshkov, 2007, Sheil and Murdiyarso, 2009, Chikoore and Jury, 2010, Goessling and Reick, 2012, Cook et al., 2011, Makarieva et al., 2009, 2013a, Dubreuil et al., 2012]. The approach taken by Spracklen et al. [2012] – reconstruction of the air trajectories from the observed wind fields and the use of daily rainfall statistics – allowed them to analyze the apparent influence of the forest on rainfall on a short-term time scale. Such an approach apparently offers detailed insights into the vegetation-rainfall relationship. The quantitative concepts that underlie the interpretation of the obtained evidence justify a comprehensive analysis.

In this note we revisit the arguments that led Spracklen et al. [2012] to conclude that the additional rain reflects a higher air moisture content resulting from forest evapotranspiration. In Section 2 we show that the quantitative conclusion about the importance of

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evapotranspiration varies with respect to the chosen time length of the air trajectories and the period of the recorded rainfall. In Section 3 we show that Spracklen et al.'s estimate of post-deforestation reduction in Amazonian rainfall is similarly a function of the selected duration of the air trajectories. We argue that, dependent as they are on arbitrary choices, these particular conclusions do not offer quantitative information about the actual atmospheric processes. The empirical findings of Spracklen et al. [2012] of a comparatively higher rainfall produced by forest compared to non-forest air are less affected by the choice of the key quantitative parameters on which their analysis was based. In the concluding section we discuss the physical variables that determine local rainfall. On this basis we suggest an alternative explanation to the observed patterns that can be tested with additional data.

2 Additional rainfall and evapotranspiration

Spracklen et al. [2012] used the Tropical Rainfall Measurement Mission (TRMM) data in the form of daily rainfall corresponding to $1^{\mathrm{o}} \times 1^{\mathrm{o}}$ degree cells. They matched each local rainfall measurement to a backward air trajectory that described the air motion during the ten days preceding the measurement, Fig. 1.

Spracklen et al. [2012] quantified air exposure to forest by integrating the leaf area index (LAI) of the vegetation traversed over the 10-day air trajectory. This magnitude, denoted ΣLAI, is measured in time units (days), as LAI itself is dimensionless:

$$\Sigma\mathrm{LAI} = \overline{\mathrm{LAI}} \times t_L, \;\; t_L \equiv \frac{L}{u} \leq t_T = 10\,\mathrm{d}. \tag{1}$$

Here $\overline{\mathrm{LAI}}$ is the mean leaf area index on the traversed territory, t_L is time spent on the terrestrial part of the trajectory by the air moving with velocity u, L is length of the terrestrial part of the trajectory, t_T is the total time length of the trajectory (including its oceanic part not shown in Fig. 1).

For each of the four tropical regions they studied, Spracklen et al. [2012] divided all the 10 days' trajectories into deciles of their ΣLAI. They found that rainfall produced in the end of trajectories with maximum ΣLAI ("forest air", top decile of ΣLAI) is several times higher than rainfall produced by the air with minimum ΣLAI ("non-forest" air, bottom decile of ΣLAI). For each trajectory they also calculated $\Sigma\mathrm{ET} = \overline{\mathrm{ET}} \times t_L$ – the total amount of moisture acquired by model-derived evapotranspiration ET into the air as it moves from the beginning of the trajectory to the point of observation. Then they calculated the mean difference ΔΣET between the forest and non-forest air trajectories and compared ΔΣET with the mean difference ΔRain in daily rainfall produced at the end of the trajectories, Fig. 1. Noting that $\Delta\Sigma\mathrm{ET}/\Delta\mathrm{Rain} > 1$ (see Table 2 in their Supplementary Information) Spracklen et al. [2012] concluded that forest-derived evapotranspiration "more than accounts" for the additional rain.

But ΔΣET (kg m^{-2}) and the difference in daily rainfall ΔRain (kg m^{-2} d^{-1}) are magnitudes of different dimensions (i.e. units). The value of ΔΣET grows with increasing time length t_L of the terrestrial part of the air trajectory, while ΔRain is calculated for an arbitrary chosen unit of time $t_R = 1$ d, Fig. 1. Being based on measures made over arbitrary periods, the ratio ΣET/ΔRain does not carry information about atmospheric processes.

3 Post-deforestation precipitation reduction

Spracklen et al. [2012] further used their findings to estimate how precipitation in the Amazon could be affected by large-scale deforestation. They calculated the dependence of rainfall on 10-days' ΣLAI, Fig. 1b.

Spracklen et al. [2012] calculated the likely LAI distribution in a deforested Amazon. Assuming that the air circulation does not change upon deforestation, they re-calculated ΣLAI

for all the trajectories. Then they recalculated the daily rainfall based on the established dependencies of local daily rainfall on ΣLAI. For example, if a trajectory was characterised by $\Sigma\text{LAI} = 10$ d but fell to $\Sigma\text{LAI} = 3$ d because of deforestation, then, according to the analysis of Spracklen et al. [2012], the rainfall at the end of the trajectory would reduce from about 9 mm d^{-1} to 4 mm d^{-1}, Fig. 1b. Having applied this procedure to the entire Amazon basin, Spracklen et al. [2012] concluded that deforestation would reduce rainfall by 12% during the wet season and by 21% during the dry season. They indicated that this reflects the loss of precipitation recycling [Spracklen et al., 2012, Electronic Methods, http://www.nature.com/nature/journal/v489/n7415/full/nature11390.html]

However, these estimates vary with respect to the chosen duration of the air trajectory t_T (and of its associated terrestrial portion t_L). Essentially, the choice of the trajectory duration determines the spatial scale at which remote deforestation influences the local rainfall observations.

For illustration consider the forest trajectory in Fig. 1a. The air covers the distance from the coast to the point of observation in $t_L = 4$ d and the forest has a mean LAI of $\overline{\text{LAI}} = 3$, such that $\Sigma\text{LAI} = 12$ d for this particular trajectory. If half of the forest closest to the coast is now destroyed and turned to a desert with $\overline{\text{LAI}} = 0$, then ΣLAI of our *4 days'* land trajectory halves to $\Sigma\text{LAI} = 6$ d, see (1). The dependence established by Spracklen et al. [2012], Fig. 1b, predicts a significant post-deforestation reduction at the point of observation O because of the decline in ΣLAI.

Now consider air trajectories with only $t_L = 2$ d. In such a case, deforestation of the coastal forest leaves unchanged the ΣLAI of the *2 days'* air trajectory arriving at point O. Over the two preceding days the air will be moving over the continental interior forest and is not affected by the coastal deforestation. As ΣLAI has not changed, one would conclude that there will be *no precipitation reduction* at point O upon the same amount of regional deforestation. Thus, the estimated impact of regional deforestation on local precipitation depends on the duration chosen by the investigators for the considered air trajectories. However, quantitative estimates based on arbitrary choices do not have a predicatve power.

4 Discussion: What determines rainfall?

To understand how forest cover influences rainfall we must understand what physical parameters determine rainfall. Rainfall occurs when moist air ascends and cools. From simple mass balance considerations precipitation rate P can be expressed as

$$P = wq(1 - \gamma_c/\gamma_s), \tag{2}$$

where w, q and γ_s are, respectively, the upward air velocity, absolute humidity and water vapor mixing ratio at the level where condensation commences and γ_c is mixing ratio at a height where it stops. In particular, if $w < 0$ (the descending air motion), any large-scale precipitation would be absent.

Ignoring turbulent admixture of moisture into the air, moisture content in the point of observation q_{O} is equal to $q_{\text{O}} = q_{\text{B}} + \Sigma\text{ET} - \Sigma P$, Fig.1. It depends not only on the cumulative evapotranspiration along the trajectory $\Sigma\text{ET} = \overline{\text{ET}} \times t_L$, but also on the initial moisture content q_{B} at the beginning *of the terrestrial part* of the trajectory and the cumulative terrestrial rainfall $\Sigma P = \overline{P} \times t_L$ that depletes the air moisture content. Remarkably, this rainfall was completely neglected by Spracklen et al. [2012] in their analyses, along with the evaporation and precipitation processes that occurred on the oceanic part of each trajectory.

Spracklen et al. [2012] noted that moisture content diminishes less in the forest than in the non-forest air from the beginning of the land part of the trajectory: $(q_{\text{fO}} - q_{\text{fB}}) > (q_{\text{nO}} - q_{\text{nB}})$. However, three additional requirements must be met in order to demonstrate that the additional rain is explained by the air's higher moisture content due to forest evapotranspiration. First, the intensity of convection (described by vertical velocity and the

completeness of condensation in the column) must be equal at the point of observation for the forest and non-forest air. Second, q_{O} must be higher in the forest versus non-forest air ($q_{\mathrm{fO}} > q_{\mathrm{nO}}$). Third, $\Sigma\mathrm{ET}$ (and not q_{B} or ΣP) must solely determine this difference.

(Such an analysis would certainly be difficult. One set of complications are due to the recognised deficiencies of models in adequately representing the key processes of atmospheric moisture transport. Indeed, there is a signicant mismatch between the modelled atmospheric moisture convergence and the runoff observed in at least some studies [e.g., Marengo, 2005]. It is a pertinent concern here that the moisture convergence for the Amazon basin derived from global circulation models is only half the figure actually observed. This implies that modeled parameters must be treated with caution and are likely to suffer major distortions. For example, while TRRM rainfall, wind directions and LAI are empirically observable variables, evapotranspiration ET is model-derived. If the models underestimate the real moisture convergence but satisfactorily reproduce rainfall, this would mean that evapotranspiration is systematically overestimated.)

Noting that any of parameters in (2) might account for the rainfall differences between the forest and non-forest air, we can propose an alternative, and fully consistent, explanation for the empirical patterns established by Spracklen et al. [2012]. Recently we have proposed that natural forest cover can lead to low atmospheric pressure. The mechanism derives from the subtle influences of atmospheric moisture, evaporation and condensation – in brief the areas with the highest evaporation drive upwelling and condensation, that induces low pressure and draws in most air from elsewhere leading to a net atmospheric moisture inflow to the continent from the ocean (see [Makarieva and Gorshkov, 2007] for the basic ideas and [Makarieva et al., 2013b] and references therein for a fuller account of the physical principles behind it). Evidence for these mechanisms has already come from a number of studies showing how rainfall over deforested areas tends to decrease exponentially with increasing distance from the ocean, while it stays more or less constant over forests [Makarieva and Gorshkov, 2007, Sheil and Murdiyarso, 2009, Makarieva et al., 2009, 2013a].

The empirical findings of Spracklen et al. [2012] are consistent with this interpretation and mechanism. Forest air will produce more rain because it is most often associated with low pressure systems (ascending air motion $w > 0$, high rainfall), while the air that has arrived from more arid regions should be more often associated with high pressure systems (descending air motion $w < 0$, low rainfall). This approach underlies a different role for forest evapotraspiration in driving rainfall patterns. The large-scale pressure gradients that drive the condensation-induced air motion are proportional to the intensity of local condensation and, hence, precipitation [Makarieva et al., 2013b]. In the stationary case $P = \mathrm{ET} + C$, where C is the net amount of atmospheric moisture imported to the region. Rather then merely influencing the moisture content in the air that is passing over the forest, the process of evapotranspiration can impact regional atmospheric dynamics by enhancing rainfall and thus modifying the large-scale pressure gradients. This, in turn, enhances and stabilizes precipitation in a positive feedback loop. Conversely, decreased evapotranspiration would contribute to slowing down the regional atmospheric dynamics and making it less reliable. Another spectacular mechanism by which plants can influence condensation intensity and, hence, the pressure gradients is the biotically controlled emission of biogenic condensation nuclei [e.g., Pöhlker et al., 2012], a process also mentioned by Spracklen et al. [2012]. The key point is that deforestation can erode terrestrial low pressure zones on land and thus lead to a greater decline in rainfall than analyses of moisture recycling alone suggest. Interactions between regional pressure gradients and hydrological forest functioning await further studies.

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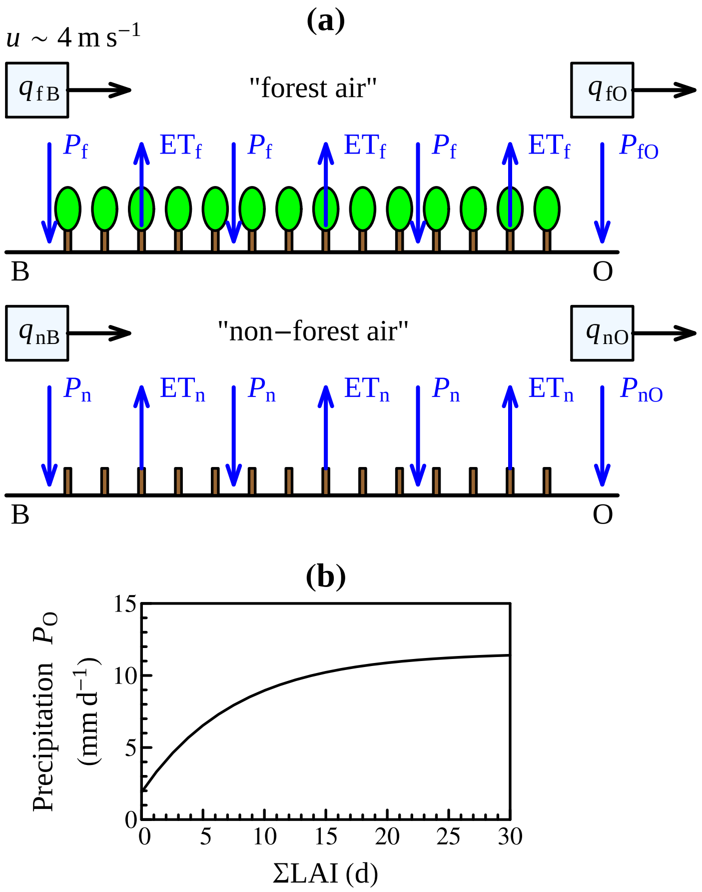

Figure 1: (a) Simplified scheme of analysis of Spracklen et al. [2012]. Two land trajectories, one over forest and one over non-forest, are illustrated to highlight key processes. Air with moisture content q_{fB} or q_{nB} at the beginning of the trajectory (B) moves for t_L days over the forest or non-forested land, respectively, then comes to the point of observation (O) where precipitation rates P_{fO} and P_{nO} (kg m^{-2} d^{-1}) are recorded. $\mathrm{ET_f}$ and $\mathrm{ET_n}$, P_{f} and P_{n} (kg m^{-2} d^{-1}) are the mean evapotranspiration and precipitation rates along the forest and non-forest trajectories, respectively. Spracklen et al. [2012] calculated $\Delta\Sigma\mathrm{ET} = (\mathrm{ET_f} - \mathrm{ET_n}) \times t_L$ and compared it with the difference in daily precipitation at the point of observation, $\Delta\mathrm{Rain} \equiv (P_{\mathrm{fO}} - P_{\mathrm{nO}}) \times t_R$, $t_R = 1$ d. Note that air moving at about 4 m s^{-1} spends about 7 hr (much less than t_R) in the point of observation ($1 \times 1^{\mathrm{o}}$ cell, approx. 100×100 km^2).
(b) The dependence of the observed wet season rainfall on ΣLAI established by Spracklen et al. [2012] for Minas Gerais, Brazil.